STUDIES ON MACHINABILITY OF NI-TI-C ALLOY USING DIFFERENT SOURCE OF ENERGY

A SYNOPSIS

Submitted by

EBENEZER G

(Reg. No. 201814294)

in partial fulfilment for the award of the degree

of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL, AERO, AUTO AND CIVIL ENGINEERING

KALASALINGAM ACADEMY OF RESEARCH AND EDUCATION
(DEEMED TO BE UNIVERSITY)

ANAND NAGAR, KRISHNANKOIL – 626 126

TAMIL NADU, INDIA.

SEPTEMBER 2022

1. INTRODUCTION

Functional materials (FMs) have been used as a promising solution to the technological problems in the society during the development of modern equipment in the field of medical, aerospace, construction, energy, etc. The FM has been claimed as a specific purpose material tailored for novel applications. The FMs have been used as a commercial alloy for the applications in the fields of aerospace, bio medical, elastic material, memory materials for dental applications. The FM has succeeded in the modern technological sectors due to its attractive and multidimensional properties. The FM properties made the materials as qualified for the common application are the following, ability to react to electrical, magnetic, optical, or biochemical stimuli and aesthetic appeal. The FMs have been used in the industrial sectors majorly for sensing and actuation. The common type of sensors manufactured in the industrial sectors includes, temperature, strain, force sensors, accelerometers and micro-positioners. Some other specific applications are piezoelectric fuel injectors in automotive, and ultrasonic imaging in medical diagnostics [1].

NiTi alloy is a functional material having notable properties such as, super elasticity, electrochemical adaptivity, wear resistance, biocompatibility, fatigue strength, elevated temperature applicability etc., [2]. In NiTi based alloy, nickel and titanium are the major constituent, further the structural properties of the NiTi system is based on the individual element [3]. The NiTi alloy shown better physical and mechanical properties, compared with the conventional metals such as Stainless steel, Tantalum, Magnesium, Iron, etc. Also, the NiTi alloy show appreciable mechanical properties in comparable with Cu-Al-Ni, Cu-Zn-Al, Ti-6Al-4V ternary alloys. The NiTi alloy properties can be improved by applying thin films over the surface or by adding alloying element based on the requirement. Some of the modified NiTi system profound in the literatures were aluminium–nickel–titanium (Al–Ni–Ti), aluminium–cobalt–nickel–titanium (Al–Co–Ni–Ti), aluminium–ferrum–nickel–titanium (Al–Fe–Ni–Ti) nickel-titanium-copper (Ni-Ti-Cu) etc.

Due to its notable mechanical property machining of such a NiTi through the traditional method is complicated, results in surface damage, dimensionally less accurate and less productivity. The real time applications of NiTi require precise and accurate machining without damage to the micro machining process [4]. The machining

requires energy to perform, some of the forms of energy utilized for machining process, viz. thermal, mechanical, chemical, and electro-chemical. In thermal based machining process, Laser beam machining, Electric discharge machining, Plasma arc machining are commonly employed. This form of machining provides precise dimensional accuracy and better surface quality. In mechanical machining techniques, there are both traditional and non-traditional ways of machining were performed. In traditional techniques, precision machining done by means of CNC based systems with hardened cutting tool for turning, drilling, etc. For miniature component micro machining process has utilized. In contra, non-traditional techniques WJM (Water jet machining), AWJM (Abrasive water jet machining), USM (Ultrasonic machining) have been employed [5].

Machining of the difficult to NiTi alloy by using both thermal and mechanical sources of energy for high precision and accurate machining is a current focus of the researchers due to the demand from the aerospace, automobile and bio medical sectors [6]. Researchers reported that the machining the NiTi might affect the surface property of the material. The surface roughness, material removal rate and tool wear rate have been predominantly studied by the researchers. The highspeed mechanical and thermal based machining end up in the large heat affected zone (HAZ). Also, machining process such as discharge machining might have a possibility of foreign metals deposition of the tool electrode material [7].

To understand the relation between the machining parameters and outcomes mathematical modelling been constructed by researchers. By using orthogonal arrays authors reduced the experiments and still found the relations with higher correlation. For optimization researchers depend on various techniques such as Principal Component Analysis (PCA) based Taguchi method, vector machine algorithm, Taguchi's method, differential evolution, response surface methodology, MOGA II, ANN, GA, Buckingham pi theorem [8]. Few researchers attempt a grey relational Taguchi's method to optimize multiple responses and arrive a single optimum condition for machining [9].

The current focus of the research is to study the machinability of the NiTi based material with the novel combination of elements. The machinability of the material studied for two forms of energy viz, thermal, and mechanical.

2. LITERATURE REVIEW

This section shows the sample of few literatures considered for the review. The availability of the literatures in the field of binary NiTi system confirmed that the NiTi alloys have been used in multiple sectors. Manufacturing of NiTi system is wide spoken topic among the researchers due to the complexity in structure and non-conformity of the required properties. Some researchers attempted to study the different manufacturing strategies and found the laser-based technology is best suited for the manufacturing process. Even though the cost of the process is high compared to the conventional casting process, the property and quality made the laser methodology at its peak [2]. Similarly, among the researchers ternary based NiTi systems caught the eye. The manufacturing strategies available for the ternary based NiTi system, NiTiCu alloy. Based on the review the researchers concluded that NiTi has more technological application, especially alloyed with Cu element. The properties of the NiTi system improved due to alloyed Cu, some of the added advantages are reduction in the temperature hysteresis, improved the shape memory effect and fatigue life. Also, NiTiCu is noted for its better biocompatibility, corrosion resistance and damping capacity [10].

Most of the literatures reported that the machining of the NiTi alloy by using the conventional methods namely turning, drilling, milling, boring, grinding etc. is concerned. The selection of tool, process parameters and machining conditions are very much vital for getting the desired outcomes. Due to hard to cut property, machining NiTi has been reported to have poor machinability characteristics like high cutting forces, greater specific cutting energy. Due to the constraints in the conventional process, nonconventional machining processes (Laser machining, EDM, Wire-EDM (WEDM), ECM and water jet machining (WJM)) are utilized for the machining of NiTi alloy [11].

Considering the machinability of the NiTi based alloy the conventional method of machining holds not good because of low thermal conductivity that leads to the heat generation between the tool and the work piece that comes in contact during machining. This eventually resulting in a high rate of tool wear and abrasivity along with a high rate of chemical reactivity with the cutting tool material [11].

Muhammad P. Jahan et. al., compared the bio compatibility of the Ni-Ti alloy with Ti-6Al-4V alloy after machining in the Micro Electric Discharge Machining(μEDM) and the authors claimed that the Ni-Ti alloys exhibits better surface morphology than the Ti alloy. On the other hand, the formation of recast layer during the machining process enhances the bio compatibility of the work piece material and increase the hardness of the machined component. The percentage of increase in hardness of the surface before and after machining is comparatively high for Ni-Ti alloy [12].

Siva kumar et. al., analysed the surface roughness and material removal rate of commercially available Ti based human implant (TL107.12) machined using the Wire Electric Discharge Machining (WEDM) considering Pulse ON time, Pulse OFF time and Voltage as parameters. The authors concluded that the influence of the Voltage is predominant for both responses viz, surface roughness and material removal rate compared to other parameters. Also, they concluded that the voltage has an inverse effect on the surface roughness [13].

During the micro drilling of conventional process there are possibilities of metallic burrs over the machined surface. The burr formation depends on the mechanism of tool kinematics and the material behaviour during the metal cutting process. During the micro machining of NiTi alloy, the tool and work interface has a major role in deciding the performance of the process with material phase transformation [14]. One of the important factors in micro drilling is tool wear rate while machining hard material. The thrust cutting force generated during the micro drilling is one of the significant reasons to blunt the cutting of the drill tool. In addition, the geometrical features of the micro cutting tool do also support in increasing the product rate and tool life [15]. In few cases, the cutting tool surface are modified with PVD / CVD / EB – PVD process to enhance the life of tool while machining difficult to cut materials. Based on the above discussions, mechanical micro drilling process is one the best technique to achieve qualified surface integrity while machining nickel-based alloys [16].

Based on the literatures the following research gaps were identified and the same reported in the next section.

3. RESEARCH GAP

The following are the research gap identified from the literatures.

1. Scant investigations were carried out for the ternary NiTi alloy, ternary NiTi system NiTiCu, NiTiCo are found in literatures, still NiTiC system and its properties were proportionately low.
2. Since the material system is new the machining characteristics of the NiTiC is not yet revealed, especially with the content of the carbon in the advanced and micro machining processes.
3. The conventional way of micro drilling in the NiTiC alloy is not found much in the literatures. The effect of the tool material and the chosen parameters on the quality of the hole drilled need further investigations.
4. From the literatures, the effect of the carbon in the microstructure during the spark erosion process and their effect on the surface characteristics is limited.
5. Electrochemical studies on the thermally machined NiTiC specimen need more attention.
6. The Laser beam drilling is known for the accuracy and the precision, but the thermal effect and the helical rotation of the laser to enlarge the hole need further investigations for the chosen material.
7. The optimization of parameters for the better outcome needs more exploration.
8. The Surface characterization of the machined surfaces needs further study.

4. OBJECTIVES

1. Procurement and the characterization of the NiTiC alloy through the Optical microscope and spectroscopic studies.
2. The machinability of the material during the following machining processes (1) Wire Electro Spark Erosion process (2) Laser beam drilling, both processes coming under the head of thermal based energy processes. (3) Mechanical based micro drilling by using the tungsten carbide drill tool.

3. Surface characterization of machined NiTiC alloy specimens using Scanning Electron Microscopy and Optical Microscopy.

4. Optimization of process parameters for better outcomes.

5. Electro chemical corrosion behaviour of the Wire Electro Spark Erosion machined specimens.

4.1 Experimental Methodology

The experimental procedure for the current research is depicted in figure 1.

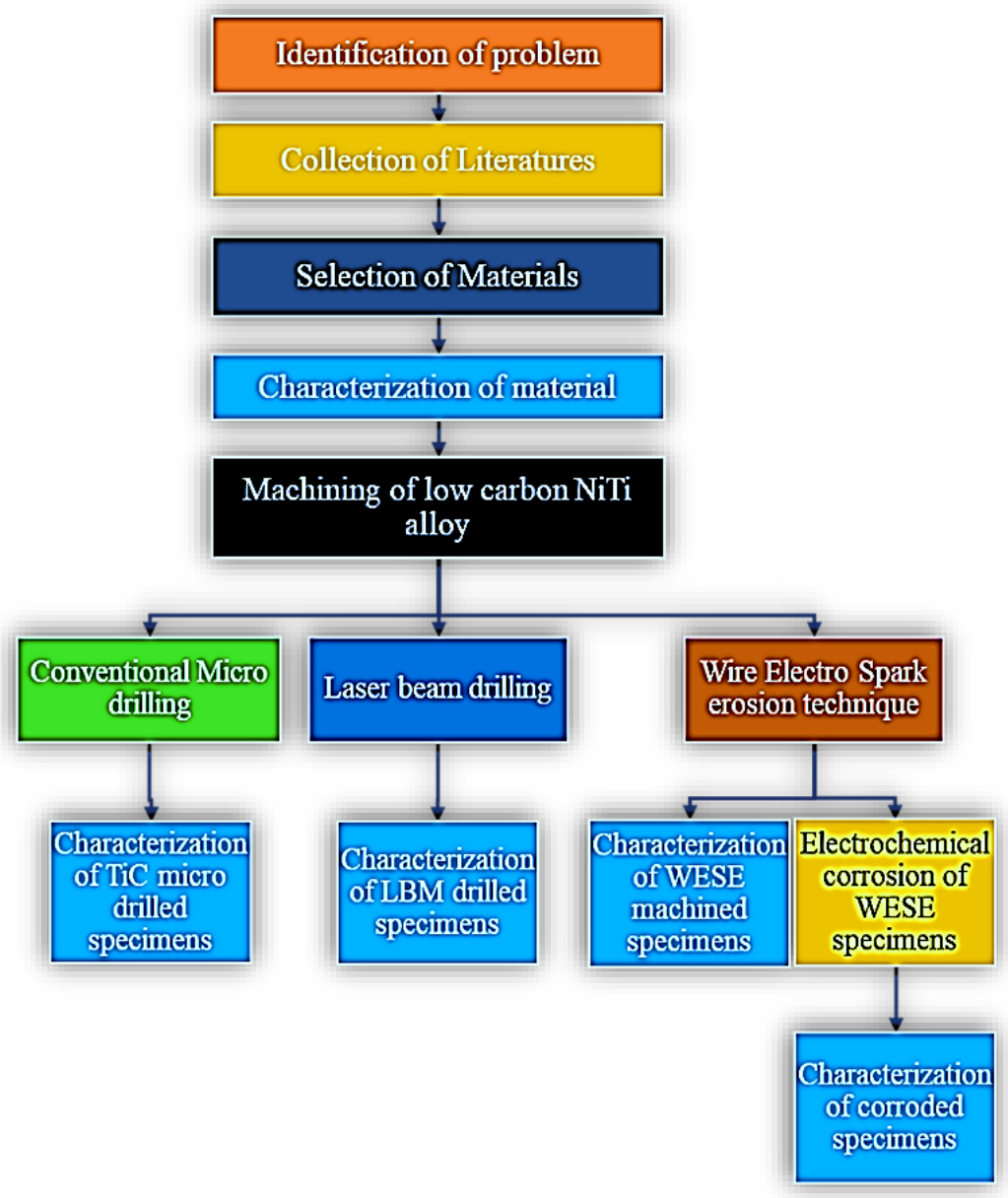
Identification of problem
Collection of Literatures
Selection of Materials
Characterization of material
Machining of low carbon NiTi alloy
Conventional Micro drilling
Laser beam drilling
Wire Electro Spark erosion technique
Characterization of TiC micro drilled specimens
Characterization of LBM drilled specimens
Characterization of WESE machined specimens
Electrochemical corrosion of WESE specimens
Characterization of corroded specimens

Figure 1. Experimental Methodology adapted for current research

4.1.1 Material and its characterization

In the current research, a commercially available NiTiC alloy was chosen for the study. The NiTiC alloy was procured from Ultimate Enterprise, Tamil Nadu, India. The shape of the procured NiTi is a circular rod of diameter 15 mm. The NiTiC alloy was cleaned with acetone to eradicate any undesirable elements over the surface. The elemental analysis was done by Omega inspection and analytical laboratory, Guindy, Chennai. The Foundry Master Pro - Optical Emission Spectrometer (OES) (Make: Oxford Instruments, Germany) was used to study and record the elemental weight percentage of NiTiCalloy and the same tabulated in table 1. The properties of the NiTiCalloy are as follows; density – 6.48 g/cm3, yield strength – 695 Mpa and ultimate tensile strength – 891 Mpa with a micro hardness 341 hv.

Table 1. Elemental weight percentage of NiTiC alloy

Element	Ni	Ti	C	Co	Fe	Al	Cr	Cu, Mo, Si
wt. %	51.80	46.356	0.052	0.352	0.188	0.134	0.469	Traces

4.1.2 Wire Electro Spark Erosion (WESE) technique

The machining of NiTiC alloy was done in ECOCUT, Electronica Wire Electrical Discharge Machining (EDM) at Precision engineering works, Madurai, Tamil Nadu, India. The Wire cut EDM machine used 0.25mm brass wire with a composition of 60% copper and 40% zinc. The commercially available brass wire was half hardened, and it was procured from Mending metals Ltd., India.

In view with the literatures, three process parameters have been chosen for the experimental study, Viz., Spark ON time (SON), Spark OFF time (SOFF) and Voltage (V). Based on literatures, a foresaid process parameters have much influence of the surface property and productivity of NiTi alloy. The NiTiC alloy was sectioned to a width of 5 mm using the WESE process as per the Taguchi's L9 experimental design.

The outcome of WESE machining process were surface roughness (SR) and Material removal rate (MRR). The SR of the machined specimens have been measured

using Surftest SJ410 surface roughness tester (Make: Mitutoyo South Asia Pvt. Ltd) instruments.

The MRR of each specimen has been calculated using the formula given in equation 1.

$$\text{MRR} = \frac{\text{Sectioned area during machining} \times \text{Width of cut}}{\text{Machining time}} \quad \ldots. \qquad (1)$$

After experimentation the machined specimens were characterized using the electron microscopy.

4.1.3 Electro chemical behaviour of the WESE machined samples

The electro-chemical corrosion was carried out in 3.5% NaCl solution. The potentiostat/ galvanostat (ACM instruments GillAC, UK) electrochemical polarization identification test was conducted with the assistance of three electrode cells positioning a reference of saturated calomel electrode, counter electrode assigned as a platinum sheet and the sample was assigned as a working electrode. ASTM G3-14 standard was followed with corrosion cell exposed area of $1cm^2$. Calomel and platinum are the two electrodes which can be used with the potential of – 250 mV to 250 mV at 1 mV/s as sweep rate to measure potential–current density. Then the exposed surface was subjected to metallurgical analysis using electron microscope and X-ray spectroscope.

4.1.4 Mechanical drilling

The micro drilling experiments have been done in multi-purpose MIKRO tools micro machining centre. The micro machining centre table is made of natural granite for high precision and damping characteristics. The maximum travel of the worktable is 200 mm (X axis) x 100 mm (Y axis) x 100 mm (Z axis). For the movement of table, precision ball screw drive system with lead screw is available. Computerized numerical control (CNC) based motion controller with the 0.1-micron resolution. In this machining study, commercially available tungsten carbide micro drill tool has been utilized to drill micro holes.

Based on the previous studies available in literatures, process parameters viz., spindle speed, feed rate have been chosen for the current study. The parameters length of cut and drill tool diameter have been maintained as constant for all experimentations. The responses measured for the micro drilling have been listed as follows: drill hole

diameter / ovality and machining time. Based on the parameters and their levels, 9 experiments were adapted. After experimentation the drilled specimens were characterized using the electron microscopy.

4.1.5 Laser beam drilling

The laser beam drilling of NiTiC alloy was done using femtosecond Nd – YAG laser machine (The machine Lee–Laser Model: 905 SLFS; from Direct Light Incorporation). The material was sliced to a thickness of 5 mm and metallurgically polished for experimentation. A blind hole is 500 μm in diameter and a square profile with the same 500 μm. For comparison, a 1000 μm hole has been made to study the thermal effect on the machined surface. After experimentation the drilled specimens were characterized using the optical and electron microscopy.

5. RESULTS AND DISCUSSION

5.1 Effect of S_{ON}, S_{OFF} and V on the Surface Roughness (SR)

SR of the machined surface increases with the increase in S_{OFF} time irrespective of the voltage (V). The S_{ON} is also directly proportionate to the SR and the variation considerably affects the SR as the S_{ON} time increases the discharge energy due the spark lasts for long period enable the WESE process to erode more surface material but the intensity at low voltage not enough to melt and flush away and forms considerable irregularities inform of recast layer over the surface which results in increase in SR. Likewise, voltage (V) also has a considerable influence in SR but in the reverse manner as V increases the SR decreases. Based on the fact as V increases the intensity of the spark energy increases melts the metal surface and clears the metal particle from the surface results in less SR.

5.2 Effect of S_{ON}, S_{OFF} and V on the Material removal Rate (MRR)

MRR of the machining process also increases with the increase in the S_{ON} time but the effect of voltage (V) on the MRR is minimum and varies with the S_{ON} time. There is a considerable influence of S_{OFF} time in the MRR. The machining time depends on the spark time and no spark time. As spark time (S_{ON}) increases, more metal been removed from the surface resulting in higher MRR compared to less S_{ON} time.

5.3 Optimization of machining parameters

The optimization is the need of any manufacturing process to increase productivity and making better-quality products. The parameter optimization is done based on Taguchi's orthogonal array approach. For better quality product SR value should be minimum nevertheless, productivity of the component depends on the MRR, and it need to be a maximum. Considering the responses SR and MRR the quality characteristics have been selected for optimization. The SR utilize the lower is better characteristics and for MRR higher is better characteristics was chosen. The signal to noise ratio (S/N ratio) were calculated based on chosen quality characteristics using the statistical package Minitab19.

5.4 Electro chemical corrosion studies

The electrochemical corrosion results of the two specimens considered for the study. The parametric setting and the surface roughness value is presented in table 2. The corrosion rate, current density (Icorr) and rest potential (Ecorr) i.e., shift from the active corrosion to passivation for samples 1 and 2 is presented in table 3.

Table 2. Parametric setting and surface roughness of the samples for corrosion test

Sample No.	Spark ON time (µs)	Spark OFF time (µs)	Voltage (V)	Surface roughness (µm)
1	110	55	20	2.2904
2	120	55	10	2.6233

Table 3. Voltamperograms results for corrosion samples

Sample No.	Ecor (mV)	Icorr (mA/cm²)	Corrosion rate (mm/year)
1	-218.87	0.010925	0.001207
2	-204.6	0.0440387	0.004555

The corrosion rate of the sample 1 is less compared to sample 2 shown in table 3. The surface roughness of the sample 1 is less compared to the sample 2. For the results it is clear the corrosion rate directly depends on the surface roughness of the machined samples. The passivation occurs for both samples, but the sample 1 corrosion potential is less and for sample 2 the corrosion potential is comparatively greater.

5.5 Effect of parameters on micro hole diameter of drilling using Twist drill

A micro drilling of 500 μm in diameter is performed on a NiTiC alloy with a tungsten carbide (WC) material micro drill tool of 495 μm in diameter. After machining, the micro drills are observed with vertical microscope to measure the drill hole diameter.

It has been observed that the drill hole close to dimension (501 μm in diameter) is achieved at a high speed (2500 RPM) machining with a minimum feed rate of 0.2 mm/min. For the same spindle speed, the drill hole diameter found increased with increase in feed rate. Obviously at a maximum feed rate of 0.6 mm/min, the diameter of the drill hole found extreme to a dimension of 546 μm in diameter. While machining, the increased feed rate will create a heavy force on the drill flute causing buckling and vibration. As a result, the deviation in cutting axis originates the non – linearity in drill hole leading to increase in drill hole diameter. This may also lead to formation maximum shear zone and metallic burrs on the top of drill hole.

At a spindle speed of 2000 RPM, the deviation in drill hole diameter found close to the 2500 RPM, found increasing with respect the increase in feed rate. For slow speed machining, the differences in drill hole diameter from 516 μm to 527 μm. It indicates that the feed rate in the range of 0.2 mm/min to 0.3 mm/min can produce an accurate drill hole with a high – speed machining. When the spindle speed gets reduced (< 2250 RPM), the outcome of the drill hole diameter starts to deviate. Therefore, the slow spindle speed can produce less error in micro drill however at a minimum feed rate of 0.2 mm/min at high spindle speed a perfect micro drill can be produced without any compromising the quality.

5.6 Effect of parameters on machining time of micro drilling using Twist drill

The machining time for micro drilling is measured and calculated with respect to input parameters using a mathematical relation given in Equation. 2. For slow spindle speed the maximum time is required to machine 500 μm in diameter for a depth of 500 μm in a NiTiC alloy is recorded as 1.78 min. The machining time found decreased with increase in spindle speed and feed rate of the cutting process. At a spindle speed of 2500 RPM with 0.6 mm/min in feed rate has a minimum machining time of 0.43 min. Minimum in machining time is one of the important key factors to increase the

production rate. To predict the machining time of the proposed design of experiments, a Gaussian elimination method is used to find a mathematical equation to compare and find the machining time for unknown parameters. The regression equation derived from the experimental design is given in Equation 3.

The machining time (Tm) equation used to calculate from the input process parameter is given below:

$$Machining\ Time\ (Tm) = \frac{length\ of\ drill\ hole}{Spindle\ Speed\ x\ feedrate}\ (\text{min}) \quad \ldots\ldots \quad 2$$

The regression equation derived from the Gaussian elimination method for the input process parameter is given below:

$$Machining\ Time\ (Tm) = 136.121\ S^{-0.803}\ f^{-0.928}\ (\text{min}) \quad \ldots\ldots \quad 3$$

Where, the length of micro drill hole is 500 µm, spindle speed (S) and feed rate (f) are the input process parameters designed for the micro drilling of NiTiC alloy.

5.6 Tool wear analysis of Twist drilling

The tungsten carbide (WC) micro drill tool bit after machining the NiTiC alloy at 2500 RPM with 0.2 mm/min. Actual diameter of the WC micro drill tool is 495 µm and after machining the NiTiC alloy for 1.2 min the tool found worn to a diameter of 492.2 µm. The cutting nose of the drill tool had a severe deformation due to friction between the NiTiC alloy and the WC micro drill. The micro hardness of the work material NiTiC alloy is 341 Hv and the micro hardness of the WC micro drill tool is 639 Hv. Hence the selection of cutting tool has supported to remove the bulk material from work piece with less wear rate.

5.7 Micro Drilling using of laser beam machining

The micromachining of round and square holes on NiTiC was discussed in this section. The round hole with a size of 500 µm diameter and the square hole of 500 µm were drilled. The three holes were made under the same condition to enhance repeatability and accuracy. The round hole diameter increased with an average diameter of 552 µm. The increase in dimension is due to the influence of laser scans. The helical

force generated by the laser beam has influenced the dimensional variations. In general, laser machining follows the conventional single shot or percussion drilling process. The laser pulse induces the material ablation during machining, and the controlled target force maintains the variation in drill diameter. The beams are under feedback control in the short-pulse laser machining, and the beam passes through the dove prism. The drill hole in concentric and ovality were also guaranteed to be reduced like conventional/long pulse laser machining.

Similarly, the square hole has a dimensional variation of 585 μm. The main reason for the change in accuracy from square hole to round hole is the sharpness (taper) of the laser beam generated. As there is a change in coordinate (vertical to horizontal) and if there is a wide difference in work material thickness, the slit of the micro-hole causes taper in the laser beam leading to a change in dimensional accuracy. Change in locus rotation was controlled in round morphology compared to the square hole. Similarly, the increase in diameter has minimum error as the locus rotation concentrates on the focal axis. In addition, the square hole proved maximum material removal due to linear movement of the laser pulse in terms of profile dimension. During the spiral/helical movement of the beam, the level of intensity will be less and found to whirl. However, the level of intensity in the flat wall is maximum, and material removal is increased.

The increase has influenced the difference in scan rate in the diameter of the micro drill. On keen observation, the root of the drill has been noticed with repeated ablation micro voids. It is also clear that the increase in diameter and track of laser flow has higher accuracy than the minimum diameter. When the diameter of the drill hole increases, the laser ablation supports maintaining the accuracy of the dimension in track with laser rotating locus. Therefore, the scan rate impacts the micro drill using short-pulsed laser machining. The machined surfaces were metallurgically polished to observe the influence of heat energy and hole morphology to understand the details of the machining process.

Therefore, a better surface finish is achieved with less wavelength and the intensity of thermal load over the cutting area. After metallurgical polishing, the laser machined surface and appropriate etchants were observed to evaluate the surface effect through an optical microscope. The effect of laser machining with a process condition;

laser power – 2500W, laser scan rate – 3 mm/min, gas pressure – 13 bar, and nozzle diameter of 1.7 mm. During machining with the conventional laser process, heat energy is generated due to continuous (long) pulse interaction with the base metal.

6. RESEARCH FINDINGS

The following were the research findings based on the experimentation results and the characterization of the machined specimens.

6.1 Summary of experimental and characterization studies of wire electro spark erosion technique

The SR, MRR and metallurgical characterization of Ni-Ti alloy machined using wire electro spark erosion technique and the following conclusions were made.

1. The S_{ON} time is a predominant parameter influencing both the surface roughness (49.44%) and material removal rate (86.70%).
2. The developed empirical relation between the process parameters (i.e., S_{ON}, S_{OFF} & V) and machining attributes (i.e., Surface roughness and Material removal rate) is accurate and the model is significant at 95% confidence limit.
3. The S_{ON} time is directly proportional to the surface roughness and Voltage (V) is inversely proportional to the surface roughness of the machined component.
4. The S_{ON} time is directly proportional to the material removal rate and other two parameters S_{OFF} time and Voltage (V) have less contribution towards the material removal rate.
5. The optimum setting for smaller surface roughness and larger material removal rate is found out using Taguchi's method.
6. The SEM characterization reveals that there is a micro crack and the micro voids over the surface of the material. The recast layer intensity increases with the increase in the SON time this may be due to the deposition of melted metal over the material surface.
7. The Voltage have reverse characteristics on the intensity of the of recast layer, i.e., as voltage increase intensity of recast layer decreases.
8. The oxygen on the surface found during the elemental analysis increase with the decrease in S_{ON} time.

6.2 Summary of electrochemical studies of WESE machined specimens

1. The machined samples show better passivation is resulting in the better corrosion resistance.
2. The SR of the machined surface greatly influence the corrosion resistance of the material.
3. Higher the SR value lower the corrosion resistance and vice versa.

6.3 Summary of experimental and characterization studies of micro drilling using laser beam machining

The functional material NiTiC alloy micro drilled using laser beam technique and the following summary were made.

1. The round hole machined with a short pulse has better accuracy than the square hole. The average difference in the round hole is 552 μm, and the square hole is 585 μm.
2. However, the rotating locus for the short pulse has removed the minimum material, and the dimension is closer to the design.
3. The influence of pulse in laser cutting has been studied in terms of surface quality. A long pulse laser has induced the material with maximum heat energy. The width of the heat-affected zone was wider to a case depth of 150 μm.
4. In short-pulse laser, the material removal is in the form of ablation. The heat energy generated during machining is completely eradicated, and the material is removed because of the force generated by the short pulse.
5. It has been confirmed that the short-pulse laser machine has physical ablation in the form of shear to machine the material. Therefore, short-pulse laser machining is recommended for the micromachining of hard material.

6.4 Summary of experimental and characterization studies of micro drilling using conventional mechanical drilling

The experimental investigations on micro drilling of NiTiC alloy with WC drill bit, the summary of results are as follows.

1. The high – speed machining at a spindle speed of 2500 RPM is a justifiable parameter to produce an average diameter of 501 μm drill hole close to

design diameter (500 µm) and it has been achieved with a minimum feed rate of 0.2 mm/min.

2. As increasing the feed rate, the drill hole diameter was found to increase with 501 µm for the same spindle speed of 2500 RPM with a maximum feed rate of 0.6 mm/min.
3. The dynamic fluctuation increases have induced the drill tool in the form of tool buckling and outing.
4. The drill open diameter faces maximum shear and material deformation like chip formation and burring.
5. The thrust force and fluctuation in cutting drill bit, the tool wear found drastic in the cutting-edge material shear during the cutting process adheres on the path of drill flute.

7. ORGANIZATION OF THESIS

Chapter 1: This chapter illustrate about the basics of functional material and their manufacturing strategy. The NiTi system of material and the application if the material in the field of aerospace, automobile, etc. Further the chapter presents the machining methodologies of the NiTi system of materials.

Chapter 2: This chapter describes a detailed literature study on the recent research on the NiTi system of materials in the field of machining and micro drilling. The research gap initiated from the detailed literature survey and the objectives were frame. Based on the objectives the proposed research methodologies were developed.

Chapter 3: This chapter explains about the candidate material and process parameters for the experimentations. Also, explains the methodology of experimentation and its equipment's. The measurement and characterization methods and procedure for investigation also discussed in detail.

Chapter 4: In this chapter, briefly explains the study of machining of the NiTiC system by using the WESE process. The mechanism of the machining and the outcome was also discussed with the help of microscopic images, spectrometric images and plots.

Chapter 5: In this chapter, briefly explains the study of electrochemical behaviour of the NiTiC system machined by WESE process. The mechanism of the electrochemical behaviour and the outcome was also discussed.

Chapter 6: In this chapter, briefly explains the study of machining of the NiTiC system by using the Twist drill tool. The mechanism of the machining and the outcome was also discussed with the help of microscopic images, spectrometric images, and plots.

Chapter 7: In this chapter, briefly explains the study of machining of the NiTiC system by using the laser beam machining. The mechanism of the machining and the outcome was also discussed with the help of microscopic images, and plots.

Chapter 8: Based on the results and discussion, the conclusions are made for the research work and the future scopes of the work were discussed in this chapter.

REFERENCES

1. Vilarinho PM, Functional Materials: Properties, Processing and Applications, *Scanning Probe Microscopy: Characterization, Nanofabrication and Device Application of Functional Materials*, (2005), 3–33.

2. Wang X, Kustov S, Van Humbeeck J, A Short Review on the Microstructure, Transformation Behavior and Functional Properties of NiTi Shape Memory Alloys Fabricated by Selective Laser Melting, *Materials*, **11** (9) (2018), 1683.

3. Li Q, Zeng Y, Tang X, The applications and research progresses of nickel–titanium shape memory alloy in reconstructive surgery, *Australasian Physical & Engineering Sciences in Medicine*, **33** (2) (2010), 129–136.

4. Sharma N, Jangra K, Raj T, Applications of Nickel-Titanium Alloy, *Journal of Engineering and Technology*, **5** (1) (2015), 1.

5. Kaya E, Kaya İ, A review on machining of NiTi shape memory alloys: the process and post process perspective, *The International Journal of Advanced Manufacturing Technology 2018 100:5*, **100** (5) (2018), 2045–2087.

6. Petrini L, Migliavacca F, Biomedical Applications of Shape Memory Alloys, *Journal of Metallurgy*, **2011** (2011), 1–15.

7. Kulkarni VN, Gaitonde VN, Karnik SR, Manjaiah M, Paulo Davim J, Machinability analysis and optimization in wire EDM of medical grade NiTiNOL memory alloy, *Materials*, **13** (9) (2020), 2184-2189.

8. Sonawane SA, Kulkarni ML, Optimization of machining parameters of WEDM for Nimonic-75 alloy using principal component analysis integrated with Taguchi method, *Journal of King Saud University - Engineering Sciences*, **30** (3) (2018), 250–258.

9. Abidi MH, Al-Ahmari AM, Umer U, Rasheed MS, Abidi MH, Al-Ahmari AM, et al., Multi-objective optimization of micro-electrical discharge machining of nickel-titanium-based shape memory alloy using MOGA-II, *Meas*, **125** (2018), 336–349.

10. Mohammed S, Qadir R, Kök M, Qader IN, A Review on NiTiCu Shape Memory Alloys: Manufacturing and Characterizations, *Journal of Physical Chemistry and Functional Materials*, **4** (2) (2021), 49–56.

11. Dash B, Das M, Das M, Mahapatra TR, Mishra D, A concise review on machinability of niti shape memory alloys, *Materials Today: Proceedings*, **18** (2019), 5141–5150.

12. Jahan MP, Kakavand P, Alavi F, A Comparative Study on Micro-electro-discharge-machined Surface Characteristics of Ni-Ti and Ti-6Al-4V with Respect to Biocompatibility, *Procedia Manufacturing*, **10** (2017), 232–242.

13. kumar S, Khan MA, Muralidharan B, Processing of titanium-based human implant material using wire EDM, *Materials and Manufacturing Processes*, **34** (6) (2019), 695–700.

14. Kuppuswamy R, Yui A, High-speed micromachining characteristics for the NiTi shape memory alloys, *International Journal of Advanced Manufacturing Technology*, **93** (1–4) (2017), 11–21.

15. Azim S, Gangopadhyay S, Mahapatra SS, Mittal RK, Singh RK, Role of PVD coating on wear and surface integrity during environment-friendly micro-drilling of Ni-based superalloy, *Journal of Cleaner Production*, **272** (2020), 122741.

16. Imran M, Mativenga PT, Gholinia A, Withers PJ, Assessment of surface integrity of Ni superalloy after electrical-discharge, laser and mechanical micro-drilling processes, *International Journal of Advanced Manufacturing Technology*, **79** (5–8) (2015), 1303–1311.

LIST OF PUBLICATION

1. **Ebenezer, G.,** Adam Khan, M., Chellaganesh, D., & Haider, J. Assessing Machinability and Surface characteristics of a Shape Memory Alloy (SMA) Processed through Wire Electro Spark Erosion Method. *Archives of Metallurgy and Materials*, **67** (3) (2022) 921-930.
2. **Ebenezer, G.**, Khan, M. A., Chellaganesh, D., & Jappes, J. W. Electrochemical behavior of machined Ni55Ti45 alloy by Wire Electro Spark Erosion (WESE) technique. *Materials Today: Proceedings*, **46**, (2021) 7728-7732.
3. **Ebenezer George**, Adam Khan M*, and Winowlin Jappes J T. Influence of short-pulsed laser and its thermal effect on micromachining of NiTi alloy. *SADHANA - Indian Academy of Sciences*. (Accepted)